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Mathematical Physics Branch

MISSION PLANNING AND ANALYSIS DIVISION

MANNED SPACECRAFT CENTER
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PROJECT APOLLO

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By Richard K. Osburn
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Approved: James C. McPherson
James C. McPherson, Chief
Mathematical Physics Branch

Approved: J. P. Mayer
John P. Mayer, Chief
Mission Planning and Analysis Division

TABLES

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FIGURES

POSTFLIGHT ANALYSIS OF APOLLO 6

RADAR TRACKING DATA

By Richard K. Osburn

SUMMARY

Postflight analyses of Apollo 6 radar tracking data were made to verify the unified S-band (USB) orbit determination capabilities and evaluate Manned Space Flight Network (MSFN) performance in general. Initial studies attempted to obtain the best possible estimate of the Apollo 6 trajectory. As a result of these studies, a serious anomaly in Ascension C-band range data was discovered and is now being corrected. Also noted were unexpected perturbations in the CSM trajectory. These were found to be the result of water boil-off, and it was concluded that the water boiler could seriously affect future missions. Comparisions of C-band and USB orbit determination results showed excellent agreement between the two systems. Evaluation of vectors obtained by the RTCC showed deviations greater than preflight error analyses had predicted. These were the results of the poor quality of the Ascension range data and the effects of water boiler venting.

INTRODUCTION

The objective of the Apollo 6 mission was to flight test the Apollo CM in earth orbit. A secondary objective, and the one of particular interest in the report, was to verify the capability of the USB system to support Apollo missions.

The purpose of this report is to present a detailed postflight evaluation of the performance of the Apollo ground navigation system during the Apollo 6 mission (AS-502), and identify weaknesses of the system. Analyses were done with the aid of the TRW/MSC Task A-108 orbit determination program (ESPOD), which fits tracking data by using a least-squares method to minimize the sum of the weighted tracker residuals. Since ESPOD is limited to processing free-flight data, analyses were limited to those portions of the trajectory which did not include burns. This constraint precluded consideration of the two earth parking orbits during which S-IVB venting had a significant effect on the

trajectory. Postflight data for this phase of the mission is available from the postflight analysis group at the Marshall Space Flight Center.

In addition to the ESPOD program, an anomaly which was discovered in the data required the use of the Jet Propulsion Laboratory (JPL) Surveyor orbit determination program to complete analyses of the trajectory. This program fits data in a manner similar to ESPOD, but has the additional capability to solve for an unmodeled trajectory perturbation in the form of a constant or time-varying acceleration.

To evaluate tracking data from the mission, a postflight best estimate of the trajectory (BET) was obtained. This trajectory was then used to evaluate all mission radar data. To determine the performance of the USB system, similar arcs of USB and C-band data were processed. Resulting state vectors were compared to determine the agreement between the two independent systems.

ANALYSIS AND RESULTS

Navigation Data Summary

Figure 1 is a summary of the low-speed tracking data received during the high ellipse phase of the Apollo 6 mission. For the postflight analyses all data obtained at an elevation of less than 5° were deleted. These deletions presented no problems since sufficient data were available to obtain an accurate estimate of the trajectory.

Evaluation Procedures

To obtain a BET, all data of a particular type, either C-band or USB, were processed together. All obviously bad data were deleted. Questionable data were evaluated by examining the residuals[a] of the suspicious data arc based on a vector from another data type (i.e., a questionable arc of C-band data would be evaluated by examining its residuals based on the S-band BET). With all bad data thus removed, the remainder were processed to obtain the BET. To provide a confidence level for the BET, the mean and root-mean-square (RMS) values of the residuals for each station were compared with expected bias and noise

[a]Residuals are obtained by considering a given data point, computing the values of the observables based on the propagated epoch vector, and obtaining the difference in the observed and computed values.

values outlined in reference 1. The above procedures were followed for both C-band and USB data. Included in the evaluation results are reasons for the deletions of all stations whose data were not included in the orbit determination runs.

To obtain the C-band BET, all three data types (range, azimuth, and elevation) were processed. Weighting was as follows:

Range, ft	90
Azimuth, deg	0.0344
Elevation, deg	0.0344

For the USB BET only doppler data were processed. This run was made at JPL on the JPL orbit determination program, and limitations on the processing time available necessitated the consideration of only Doppler data. The range and angle residuals were obtained in later runs to test the validity of the solution.

A primary objective of the mission was the evaluation of the USB system. To provide an independent verification of the system performance, vectors obtained by processing USB data were compared with those obtained by processing C-band. Since the C-band transponder was powered down at apogee, it was necessary, in order to insure the validity of the comparisons, that only USB data prior to apogee be processed in the comparison solutions. Thus, the comparison vectors were obtained from a fit of USB data prior to apogee rather than directly from the USB BET, which included USB data both before and after apogee. With a confidence level thus established for the USB solution, residual plots from the fit were examined to determine individual station performance.

Evaluation Results

The first goal of the postflight analyses of the coast ellipse data was to obtain a BET upon which further analyses could be based. Since the C-band system was the prime data source for Apollo 6, initial efforts were directed toward C-band data. These data were available, as shown in figure 1, only prior to apogee. The C-band beacon was turned off near apogee to attempt to correct a hardware problem. The problem was not corrected, but the beacon remained off for the remainder of the mission.

Figure 1 reveals four dropouts in Ascension C-band data and one in Carnarvon data. Visibility studies indicated that the spacecraft was visible at these times, but no data were received by the Real-Time Computer Complex (RTCC). Ascension reported in real-time that their

initial acquisition had been on a side-lobe of the antenna. They were asked to reacquire, which should have involved no more than a 2-minute loss of data. The 12-minute data loss was thus longer than expected. Checks with personnel at Ascension revealed that all four dropouts could be traced to problems with the on-site computer. The computer had gone down during the reacquisition procedure and again at the three remaining times when data losses were noted. The Carnarvon dropout was traced to a similar problem.

Preliminary runs confirmed that Ascension had been locked on a side-lobe of the antenna from $15^h34^m54^s$ to $15^h36^m30^s$ G.m.t. These data were deleted from all fits. Analyses also revealed an apparent range bias of approximately -400-ft in Ascension range data from $17^h25^m54^s$ to $17^h43^m12^s$. This appeared to be a problem similar to those encountered with Ascension range data during the previous two missions. The bias on these data was obvious from preliminary runs, and this segment was deleted from the fit which determined the C-band BET.

A vector obtained by processing the remaining segments of Ascension data together with all Carnarvon data appeared to fit the data reasonably well. However, comparison with the USB solution for the same period revealed the following differences in root-sum-square (RSS) position and velocity.

ΔR, ft	3447
ΔV, fps	0.51

These differences were larger than expected, and led to the belief that some of the data processed as good was, in reality, bad. Carnarvon residuals based on the USB vector indicated bias and noise values within expected limits; hence, Ascension data were suspected and were examined more closely. Two runs were made. The first fit all Carnarvon data and all good Ascension data before $17^h25^m54^s$ G.m.t. The second fit all Carnarvon data and all Ascension data after $17^h43^m12^s$. The resulting differences between the C-band fits and the USB fit were as follows:

Run 1:	ΔR, ft	1803
	ΔV, fps	0.08
Run 2:	ΔR, ft	8380
	ΔV, fps	1.61

From these differences it became apparent that the later portion of Ascension data was not consistent with other available data. These data

were deleted from the run which obtained the C-band BET. The noise and bias for all data used in the C-band BET is the same as that given in table II, which will be discussed later. The noise and bias values were nominal with the exception of Carnarvon angles, which exhibited noise levels slightly higher than expected.

To determine whether the C-band vectors, which were based only upon pre-apogee data, represented an accurate estimate of the entire coast phase trajectory, the residuals for the postapogee Carnarvon USB data were generated based on the C-band trajectory. Figure 2 is a plot of the range and Doppler residuals. Nominally, the residuals would have shown only noise about a zero mean. The particular residual signature evident in figure 2 is characteristic of an unmodeled, low-thrust, trajectory perturbation. The problem was traced to the spacecraft environmental control system (ECS). The ECS water boiler was venting continuously with an average force of 0.08 lb throughout the coast phase. This force caused the perturbations noted in the Carnarvon residuals. A detailed analysis of the Apollo 6 water boiler venting may be found in reference 2. The venting necessitated finding a method of modeling it in order to obtain an accurate estimate of the trajectory. There were no options available in ESPOD which considered venting. Hence, it was decided that the JPL Surveyor orbit determination program, which allows the user to solve for an unknown venting acceleration, would be used for the final orbit determination (OD) runs. Bill Wollenhaupt of MSC made the necessary runs at JPL. Due to time and program constraints, only Doppler data were used to determine the final BET. The long data arc and three-station geometry assure, however, that the Doppler-only estimate of the state is an accurate one. Only one point per minute was considered. The JPL program extracted the data from the raw Doppler count. Thus, it is valid to consider the data as being at the one-per-minute rate, though the RTCC rate was ten per minute. Data statistics presented in this report are adjusted accordingly.

Table I summarizes the statistics of the tracking data residuals for the three stations included in the orbit determination run which obtained the final BET. All performance appears normal with the exception of the Guam data, which exhibit noise values considerably higher than expected. Excessive noise on Guam Doppler has been noticed near reentry for both the Apollo 4 and Apollo 6 missions. The problem, which is unexplained at the present time, is being examined further and will be reported at a later date.

It is impressive to note the effect of considering the water boiler vent on the trajectory obtained by the JPL program. To determine this effect a run was made considering the same data but neglecting the unmodeled thrusting. Figures 3 and 4 are plots of the differences in RSS position and velocity between the two trajectories for various times

throughout the coast ellipse. These figures demonstrate graphically the types of errors which we might expect to see as the result of a trajectory perturbation such as the water boiler venting.

In order to obtain a valid comparison of the C-band and USB systems three runs were made. The first, fit 1, involved only C-band data. Fit 2 was based only upon USB data, and fit 3 involved both C-band and USB data. In each case the data arcs considered began at $16^h20^m00^s$ G.m.t. and ended at $18^h29^m00^s$. USB data before $16^h20^m00^s$ were eliminated to insure that the high range rates prevalent prior to that time did not magnify the effects of station location and other model errors. For each fit the solved-for epoch vector (anchored at apogee) was propagated from the end of the SPS-1 burn to apogee in increments of 30 minutes. At each point fits 2 and 3 were compared with fit 1. Differences in RSS position and velocity are summarized in figures 5 and 6, respectively. As an additional measure of the agreement between the two systems, tables II, III, and IV present the statistics of the tracking data residuals based on fits 1, 2, and 3, respectively. Expected 1σ noise and bias values, obtained from reference 1, are included in the table for comparison. By comparing the data statistics in these tables, it can be seen that the C-band and USB data are in excellent agreement.

Table V compares vectors obtained by the RTCC during the mission with those obtained from the BET obtained by the JPL orbit determination program. Differences presented are in RSS position and velocity only. Differences in the Cartesian, spherical, or orbital elements are available from the author.

CONCLUSIONS

Overall performance of the USB system during the Apollo 6 mission was a considerable improvement over previous missions. Operational errors appeared to be fewer, and the agreement between the S-band and C-band systems was better.

Serious anomalies were noted in Ascension C-band data and in the coast ellipse trajectory. The Ascension problem was discovered to be the result of a time-tagging error in the Ascension computer. This is currently being corrected. The trajectory problem was traced to water boil-off from the CSM environmental control system. The force of the boil-off caused a significant perturbation to the vehicle trajectory. The use of a radiator for cooling on future missions should eliminate most of the problem; however, the water boiler will be the backup system throughout the mission. Information provided by North American Rockwell shows that after a failure in the radiator we might expect an average

force of 0.22 lb from water boil-off (ref. 3). A force of this magnitude during a transearth trajectory could cause the vehicle to miss the reentry corridor.

Comparisons of vectors from the C-band and USB orbit determination runs showed excellent agreement. Statistics of the C-band data residuals based on the USB trajectory showed virtually no degradation from the same statistics based on the C-band vector.

Comparisons of RTCC orbit determination results with the postflight BET showed deviations greater than those predicted by preflight error analyses. These deviations were almost totally a result of the water boiler venting. The most notable areas of disagreement were during the early portions of the ellipse, when only Ascension data were being processed, and the period after $19^h00^m00^s$ G.m.t. The RTCC was forced to down-weight the apriori information several times after apogee. These times may be correlated with those vectors where improved position information is noted. As a whole, RTCC performance was degraded considerably by the venting.

TABLE I.- S-BAND NOISE AND BIAS BASED ON USB BET

Station	Data type	Number of data points in solution	Bias		Noise	
			Observed	Expected	Observed	Expected
Ascension	Doppler, Hz	60	0	0.1407	0.0118	0.0094
Carnarvon	Doppler, Hz	102	-0.0005	0.1407	0.0089	0.0094
Guam	Doppler, Hz	10	-0.0041	0.1407	0.0429	0.0094

TABLE II.- NOISE AND BIAS BASED ON C-BAND-ONLY SOLUTION (Fit 1)[a]

Station	Data type	Number of data points in solution	Bias		Noise	
			Expected	Observed	Expected	Observed
Ascension	R, ft	50	±40	1	20	11
	A, deg	50	±0.017	-0.007	0.009	0.005
	E, deg	50	±0.017	0.005	0.009	0.007
Carnarvon	R, ft	59	±40	0	20	15
	A, deg	59	±0.017	0.011	0.009	0.010
	E, deg	59	±0.017	-0.003	0.009	0.012

[a]Expected 1σ noise and bias values are from reference 1.

TABLE III.- NOISE AND BIAS BASED ON S-BAND-ONLY SOLUTION (Fit 2)[a]

Station	Data type	Number of data points in solution	Bias		Noise	
			Expected	Observed	Expected	Observed
Ascension C-band	R, ft	50	±40	-4	20	14
	A, deg	50	±0.017	-0.007	0.009	0.005
	E, deg	50	±0.017	0.005	0.009	0.007
Ascension S-band	R, ft	70	±60	0	30	32.3
	X, deg	109	±0.090	0.016	0.045	0.010
	Y, deg	109	±0.090	0.024	0.045	0.006
	Doppler, Hz	70	±0.140	-0.054	0.092	0.078
Carnarvon C-band	R, ft	59	±40	12	20	16
	A, deg	59	±0.017	0.011	0.009	0.010
	E, deg	59	±0.017	-0.003	0.009	0.010
Carnarvon S-band	R, ft		±60	0	30	8
	X, deg	58	±0.090	-0.054	0.045	0.014
	Y, deg	58	±0.090	0.028	0.045	0.011
	Doppler, Hz	58	±0.140	-0.008	0.092	0.078

[a]Expected 1σ noise and bias values are from reference 1.

TABLE IV.- NOISE AND BIAS BASED ON C AND S-BAND SOLUTION (Fit 3)[a]

Station	Data type	Number of data points in solution	Bias		Noise	
			Expected	Observed	Expected	Observed
Ascension	R, ft	50	±40	-2	20	13
C-band	A, deg	50	±0.017	-0.007	0.009	0.005
	E, deg	50	±0.017	0.005	0.009	0.007
Ascension	R, ft	70	±60	3	30	29.7
S-band	X, deg	109	±0.090	0.016	0.045	0.010
	Y, deg	109	±0.090	0.024	0.045	0.006
	Doppler, Hz	70	±0.140	-0.064	0.092	0.078
Carnarvon	R, ft	59	±40	4	20	16.
C-band	A, deg	59	±0.017	0.011	0.009	0.010
	E, deg	59	±0.017	-0.003	0.009	0.012
Carnarvon	R, ft	58	±60	-8	30	8
S-band	X, deg	58	±0.090	-0.054	0.045	0.014
	Y, deg	58	±0.090	0.028	0.045	0.011
	Doppler, Hz	58	±0.140	-0.006	0.092	0.078

[a]Expected 1σ noise and bias are from reference 1.

TABLE V.- COMPARISON OF RTCC VECTORS AND JPL BET VECTORS

Vector ID	G.m.t., hr:min:sec	RSS Position, ft	RSS Velocity, fps
ANTC062	15:23:30	2291	4.07
ACNS049	15:27:36	2209	2.36
ACNS052	15:35:48	2759	3.34
ASCC055	15:48:24	3769	2.33
ASCC057	16:09:06	4465	1.39
ACNS058	16:19:36	7863	1.81
ASCC059	16:24:42	7278	1.48
ACNS060	16:27:36	9482	1.80
CROC061	16:31:48	3766	0.57
PREC064	16:37:36	4690	0.52
ASCC065	16:38:30	4742	0.52
ACNS066	16:47:24	4713	0.52
CROC067	16:55:36	3713	0.74
PREC068	17:01:30	3790	0.81
ASCC069	17:02:42	3318	1.12
ACNS070	17:11:12	3165	1.14
CROC071	17:19:24	3127	1.20
PREC073	17:28:48	3194	1.26
CROS074	17:30:42	3395	1.29
ASCC075	17:36:30	3612	1.34
ASCC076[a]	17:45:36	3937	1.29
CROS077	17:54:30	4541	1.33
PREC078	18:04:24	5595	1.43
CROS079	18:06:12	7556	1.47
ASCC080	18:07:42	7742	1.44
CROS082	18:33:48	9526	1.25
CROS083	18:57:36	10185	1.08
CROS084	19:21:36	9457	0.86
CROS085	19:45:30	7440	2.11
CROS086	20:09:30	4910	3.42
CROS087	20:28:06	6028	4.13
CROS088	20:36:12	12950	5.54
CROS089	20:44:12	17814	5.43
CROS090	20:52:12	18935	4.12
CROS091	21:00:12	13928	3.49
CROS092	21:08:12	9195	3.63
CROS093	21:16:54	926	2.16
GWMS095	21:24:54	1053	2.31
UPDATE	21:15:33.56	11449	5.63

[a]Update base vector.

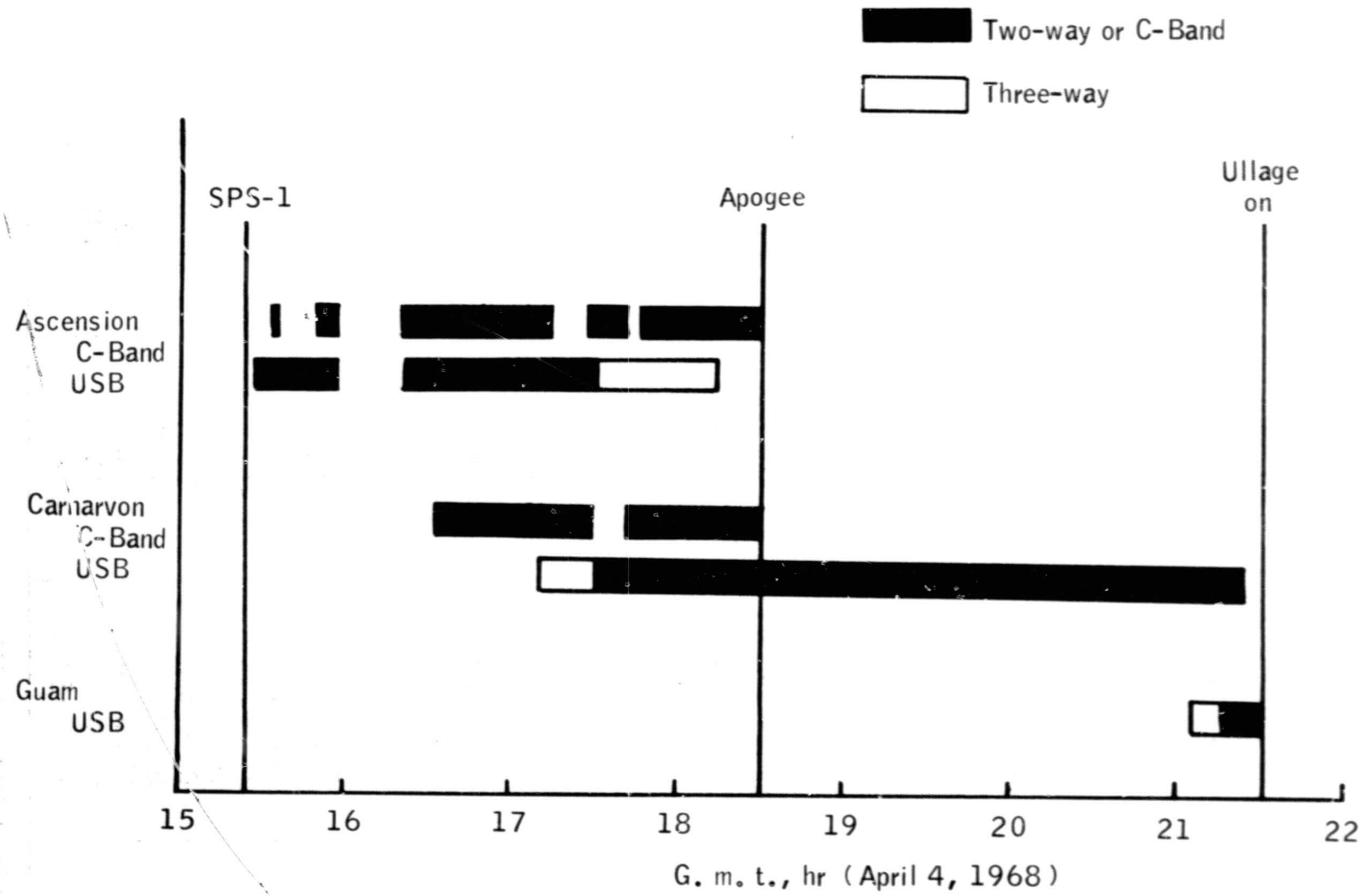

Figure 1.- Low speed tracking data.

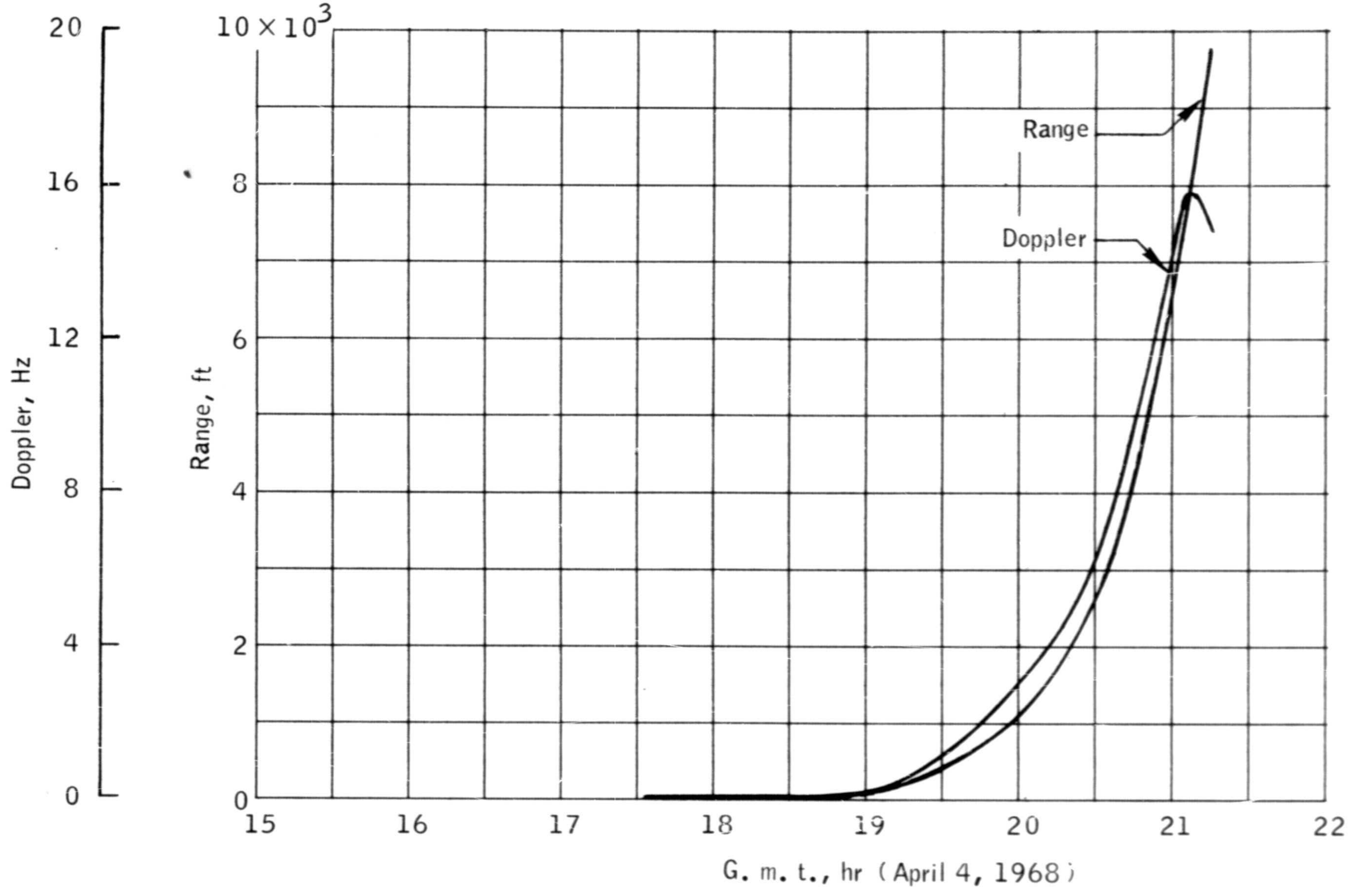

Figure 2.- Range and Doppler residuals for Carnarvon data.

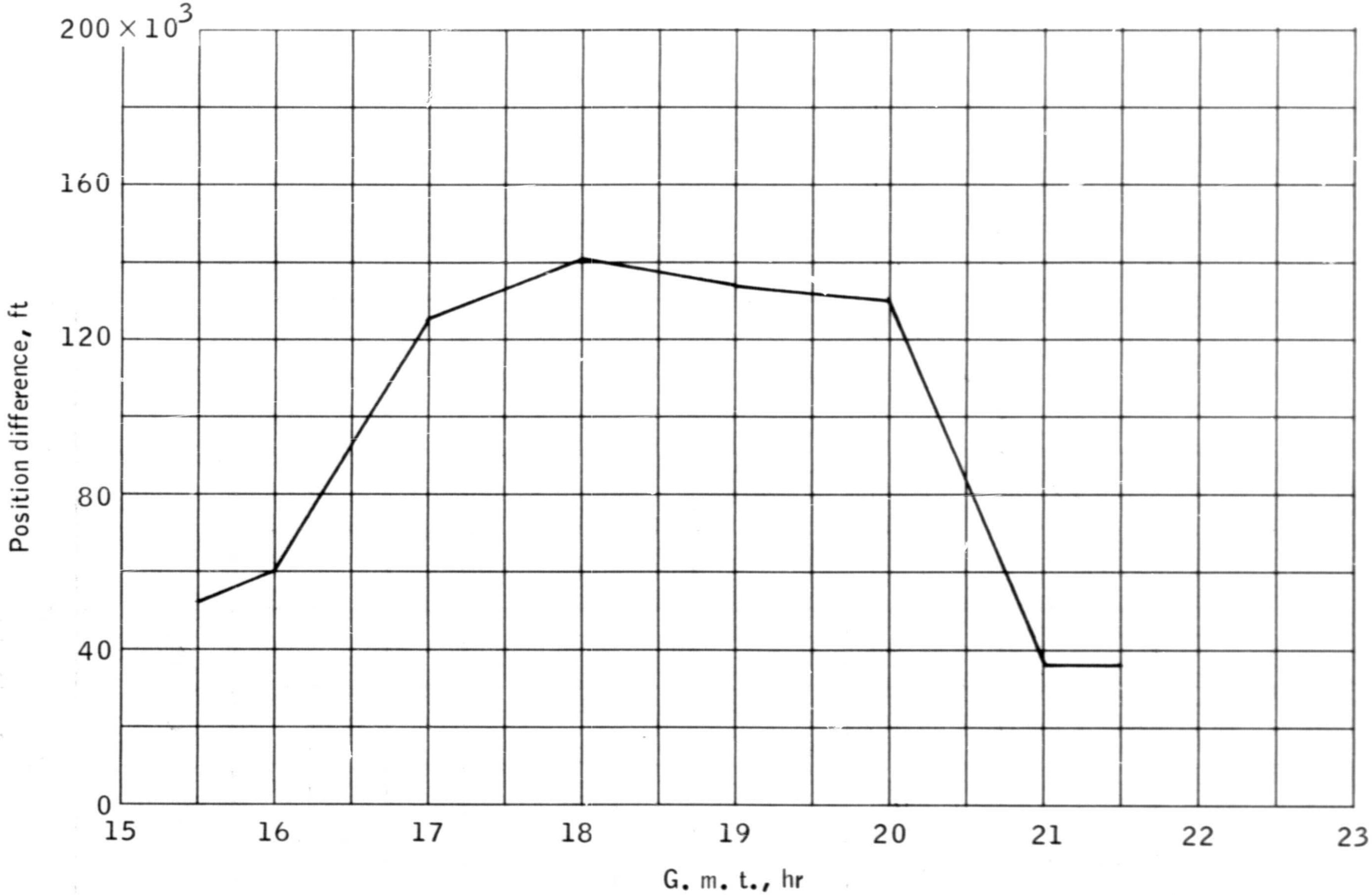

Figure 3.- Differences in the RSS position of ESPOD and the JPL program.

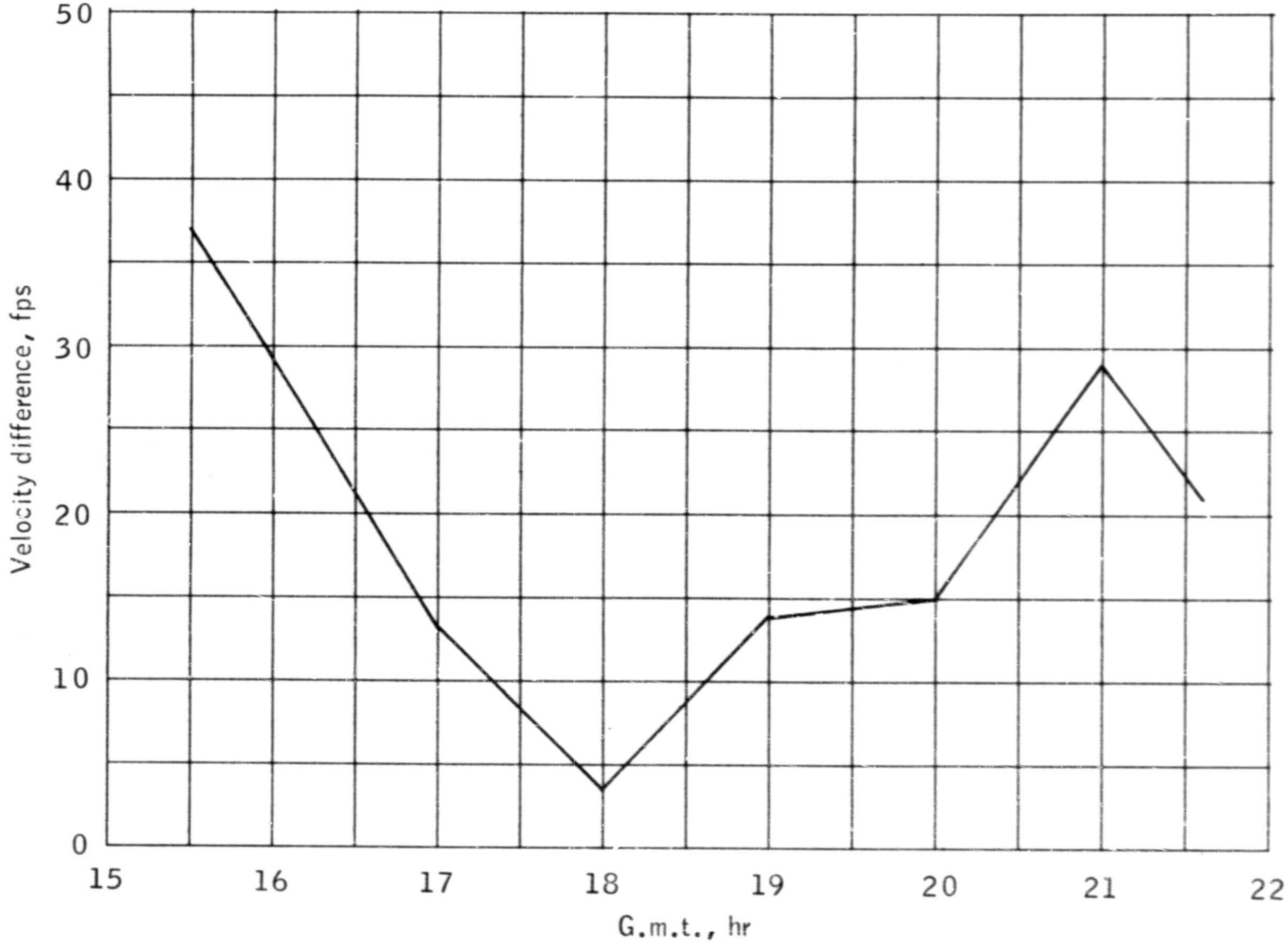

Figure 4.- Differences in the RSS velocity of ESPOD and the JPL program.

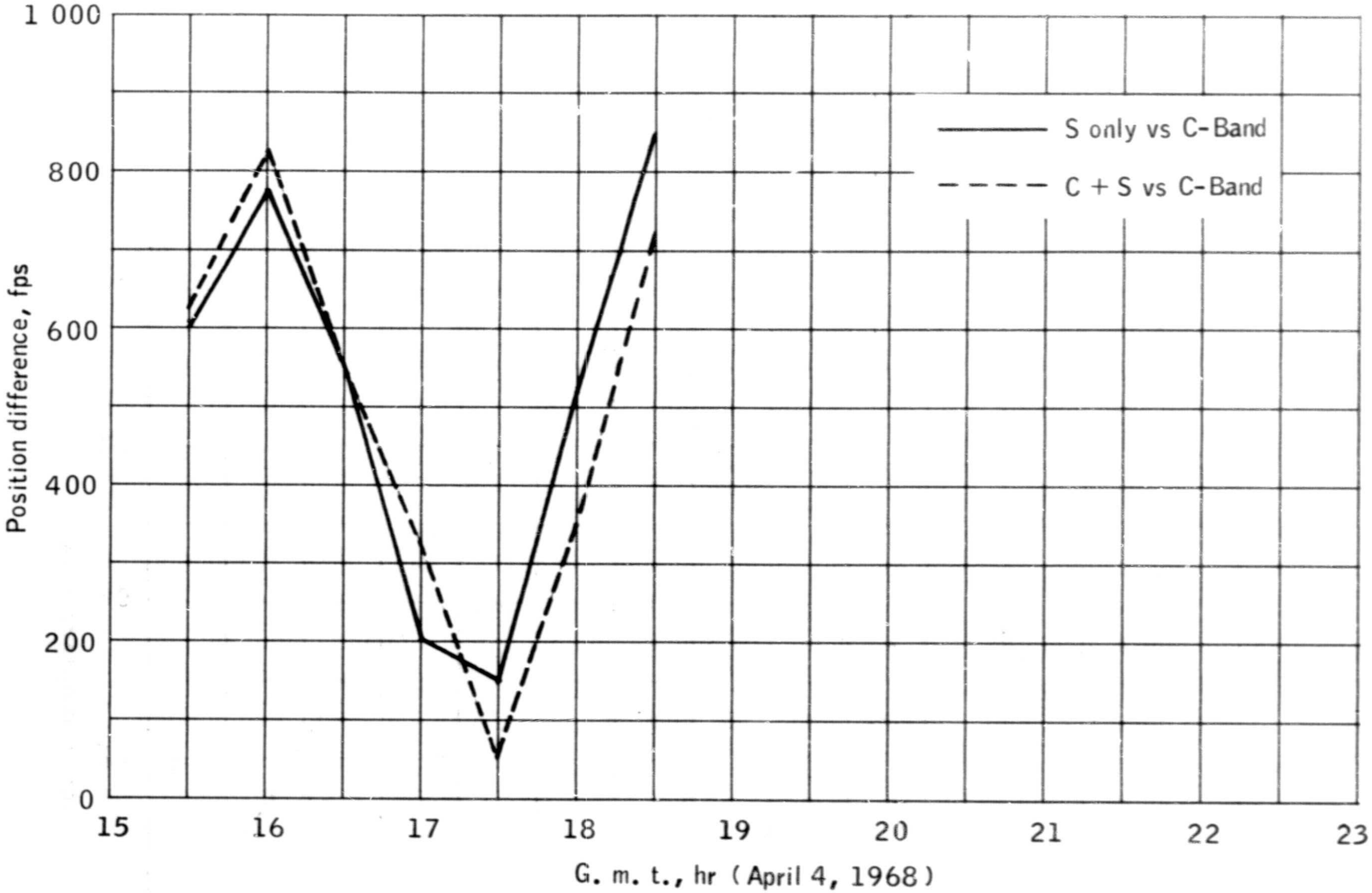

Figure 5.- Differences in the RSS position of fits 2 and 3 compared to fit 1.

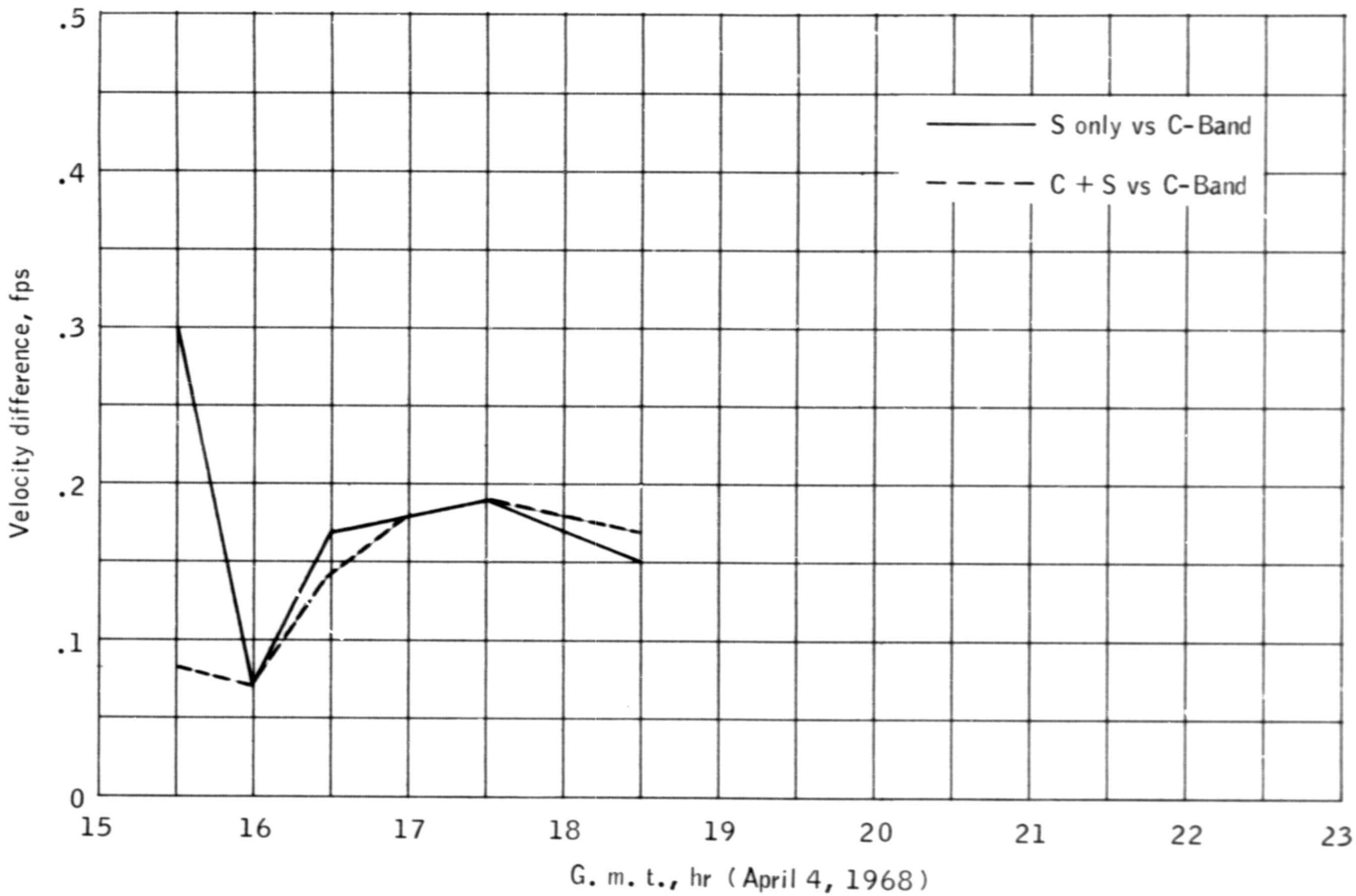

Figure 6.- Differences in the RSS velocity of fits 2 and 3 compared to fit 1.

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1. MSC-GSFS: ANWG Report No. AN-2.1, September 1, 1968.

2. Richard K. Osburn: Apollo 6 Water Boiler Venting, MSC IN 68-FM-227, September 20, 1968.

3. Thrust Induced by ECS Fluids and Fuel Cell Purge Gases, North American Rockwell Corporation Internal Letter 695-322-110-68-058, June 21, 1968.